Reducing Along-Track Stripes in OMI-Level 2 Products

Summary: In this document systematic errors in OMI-level 2 products are discussed that appear as along-track stripes. Such features appear mainly in level 2 data for the column density of atmospheric trace gases with very weak absorption features such as NO_2 and BrO but also in O_3 column data and cloud top height data which is determined from the O_2-O_2 column. The origin of the stripes is discussed in detail and correction strategies are proposed. These strategies are applied to a dedicated data set that has been reprocessed using the time-dependent-OPF approach.

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References

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[RD2]…..J. de Haan, Sensitivity analysis DOAS Spikes and Diffuser features in the Solar Spectrum Sensitivity analysis , SN-OMIE_KNMI-???, KNMI, De Bilt, 2006

[RD3]…..R. Dirksen, Analysis of dIRRAD using in-flight irradiance data, TN-OMIE-KNMI-741, issue 1, KNMI, De Bilt, July 28, 2006

[RD4]….Q. Kleipool, Transient signal flagging algorithm definition for non-radiance data, issue 2, TN-OMIE-KNMI-718, KNMI, De Bilt, July 12, 2005

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Acronyms

ADC	Analogue-to-Digital Converter
dIRRAD	delta irradiance correction
DOAS	Differential Optical Absorption Spectroscopy
GPDS	Ground Data Processing Software
ODPS	OMI Data Processing System
OMI	Ozone Monitoring Instrument
OPF	Operational Parameter File
PGE	Product Generation Executable
QVD	Quartz Volume Diffuser
RTS	Random Telegraph Signal
SNR	Signal-to-Noise Ratio
TMCF	KNMI Trend Monitoring and Calibration Facility

Terms

Spike	A spike is an outlier values in intensity spectra as a function of the wavelength.
Stripe	A stripe refers to outlier values in atmospheric column data as a function of the row, or viewing angle.

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1 Introduction

1.1 Purpose of the document

The column density data for various atmospheric trace gases retrieved from OMI measurements exhibit systematic enhancements at specific viewing angles or rows. These features remain rather constant throughout many orbits and appear as along-track stripes. Stripes are observed in the atmospheric column data of trace gases with very weak absorption features such as NO_2 and BrO but also in O_3 column data and cloud top height data which is determined from the O_2-O_2 column. In this report the origin of these features is explained using the NO_2 product as a reference, and strategies are proposed to reduce these artefacts in OMI-level 2 products.

1.2 Stripes

NO_2 column densities are retrieved from OMI measurements of the solar irradiance over a volume diffuser and the earth shine radiance in the visible (405 nm to 465 nm) using a DOAS approach [RD1]. A solar irradiance measurement comprises about 52 individual measurements with a solar elevation angle ranging from -3º to 3º that are averaged and stored in an irradiance data product. Such solar irradiance measurements are performed on a daily basis. One irradiance product is nominally used for the operational processing of earth shine radiance measurements of one day (~14 orbits). Figure 1.1 shows NO_2 vertical column density data from earth shine radiance data of orbit 4940 and from solar irradiance data of orbit 4933. The vertical column is derived from the slant column using the initial guess air mass factors for clear sky conditions. The retrieved vertical column values exhibit systematic enhancements at specific viewing angles throughout the orbit. These features are typically one across-track pixel broad and appear as along-track stripes. The true spatial distribution of the NO_2 column density above the Sahara desert can be assumed to be smooth due to the absence of sources.

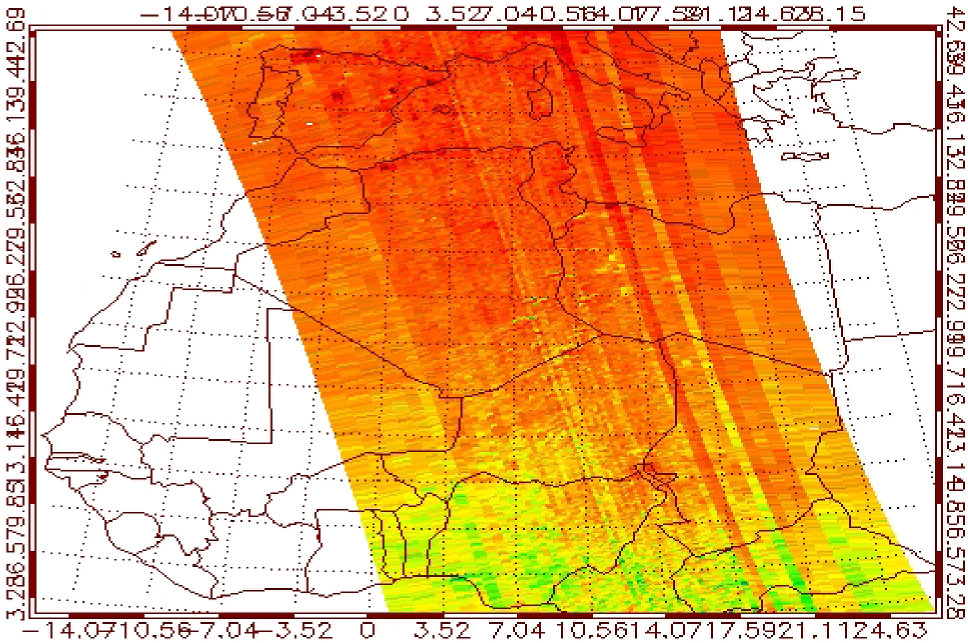

Fig. 1.1 NO_2 vertical column density from earth shine radiance data from orbit 4940 and solar irradiance data from orbit 4933.

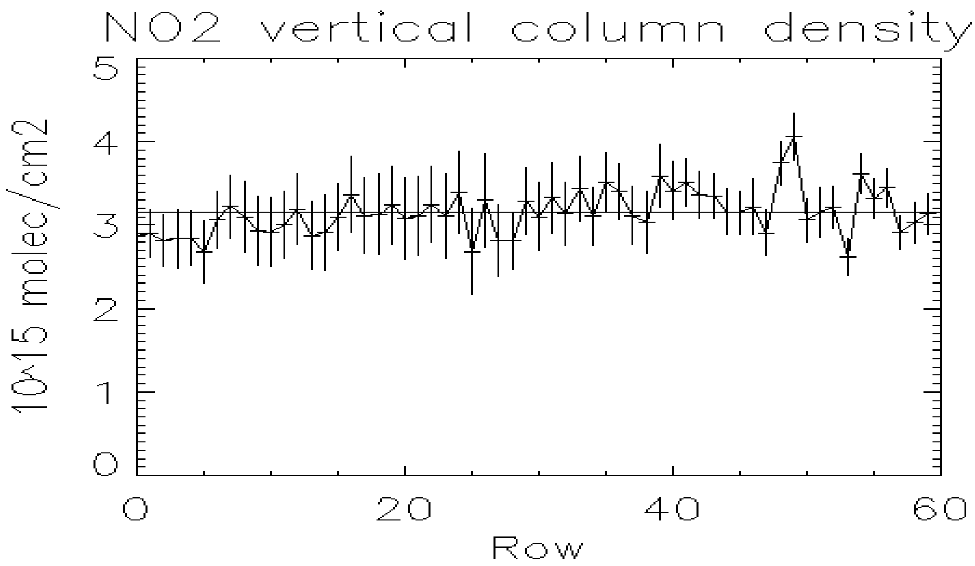

Fig. 1.2 Along-track median of the NO_2 vertical column data shown in Fig. 1.1 (molec/cm^2). The along-track variability is depicted as error-bars indicating the 2σ-environment of the standard deviation.

The enhancement is considered as systematic when the deviation of the along-track median from the average is larger than the along-track standard deviation (Figure 1.2). A prominent stripe with an amplitude exceeding 20% is found at rows 48 and 49. Stripe patterns with peak to peak amplitudes of 20 % are commonly found in NO_2 columns density data processed using the operational parameter file (OPF) version 17. Other level 2 data products, e.g. for the O_3 column density or the cloud top pressure, exhibit a stripe pattern with typical amplitudes of a few percent peak to peak. The amplitude of stripes is mostly comparable or lower than the retrieval error which is on the order of 10 % in the case of the NO_2 column density. Nevertheless, the systematic nature of these features deteriorates the retrieved data. This document discusses strategies to reduce the stripes.

2 What causes stripes?

A first indication about the origin of the stripes can be derived from the behaviour of the stripe pattern: The along-track stripe pattern in the retrieved vertical columns remains largely constant for the radiance data that are processed with the solar spectra from the same irradiance measurement. In general, we observe that the stripe pattern from different radiance data is very similar if the data are processed with the same irradiance product. In contrast, the stripe pattern changes drastically when using different irradiance data even when the same radiance product is used. This suggests that the origin of the stripes should be sought in the irradiance rather than in the radiance spectra. This assumption is supported by the fact that the signal level of the irradiance measurements is by a factor of about 4 lower than the signal level of the radiance measurements. Additive noise components and additive errors such as dark signal errors have therefore a relatively larger impact on the irradiance data as compared to radiance data. Errors in the retrieved column data caused by such errors are constant for all orbits processed with the same irradiance data and appear as stripes.

Regarding the temporal variability of the stripe pattern it is found that stripe patterns that are associated with irradiance products from consecutive days are well correlated. For time lapses of ten days or more the stripe pattern are largely uncorrelated. The amplitude of the stripe pattern tends to increase in time. Using updated background calibration data reduces the amplitude. This suggests that stripes are caused mainly by time-dependent properties of the OMI instrument that affect the background calibration.

We note that it is difficult and sometimes even impossible to identify the spectral features in individual irradiance spectra that are responsible for stripes. The analyses shown in the following are therefore mainly based on comparisons of various spectra.

2.1 Dark signal

The intensity measurement of each pixel of the detector array is influenced by a dark current. Dark signals have to be subtracted from the total signal in order to obtain calibrated intensity values. This applies to earth shine radiance as well as to solar irradiance measurements. Particle hits on the detector change the dark current of individual pixels temporally or permanently. Pixels showing a randomly changing dark signal are flagged as random telegraph signal pixels (RTS) [RD6]. Pixels that exhibit a transient change of the dark signal due to a particle hit but behave normally afterwards are flagged as erroneous for individual measurement frames [RD4, RD5].

Changes in the dark signal (Fig. 2.1, left panel) map on the irradiance spectra (right panel). Since these changes are specific for individual pixels, they appear as spikes in the measured spectra. For the sake of clarity, in this document the term ***spike*** refers to outlier values in intensity spectra as a function of the wavelength, whereas the term ***stripe*** refers to outlier values in atmospheric column data as a function of the row, or viewing angle. Prominent spikes have amplitudes of about 1 %. Some spikes remain rather constant after they appear, whereas the amplitude of other spikes decreases with time.

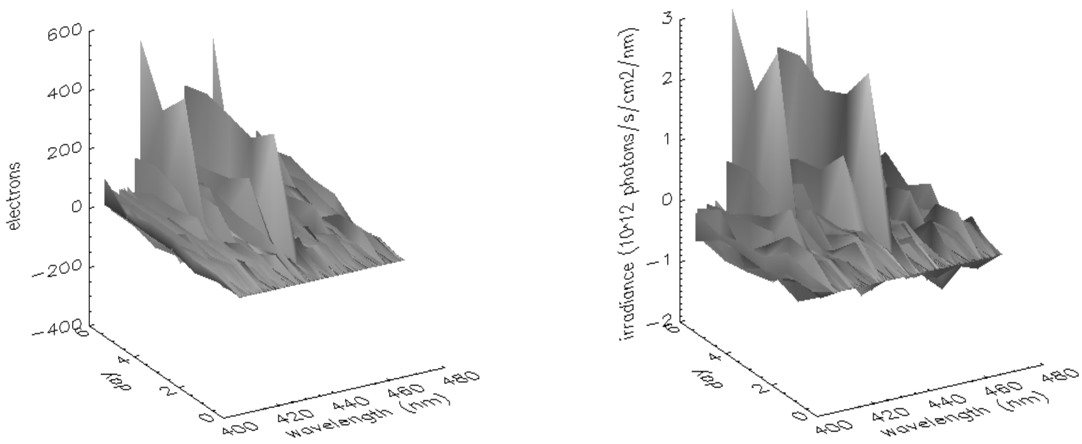

Fig. 2.1 Changes in the dark signal (left) and the elevation-angle-averaged irradiance spectra (right) over a period of 7 days. The deviation from the reference spectrum (1st day) is shown for the wavelength region 405 nm to 465 nm at viewing angle 41.

Changes in the dark signals introduce additive errors in both irradiance and radiance spectra as long as the dark signal data used in calibration are not updated. Such an update can be seen in Fig. 2.2 at day 16, where the amplitude of existing spikes is significantly reduced and new spikes appear. The spectral position of the new stripes seems to be independent from the spectral position of the old ones. The amplitudes and the positions of spikes change in time and differ from row to row (Fig. 2.2).

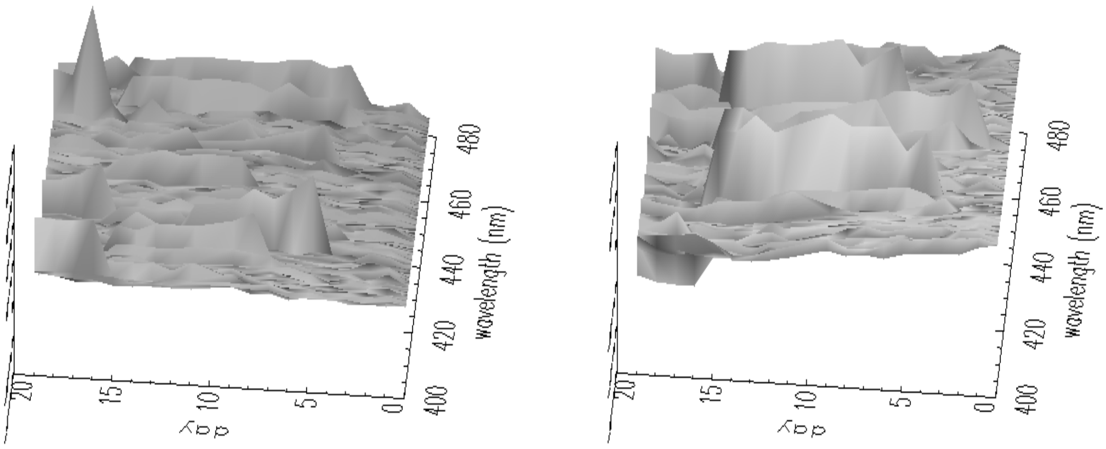

Fig. 2.2 Changes in irradiance spectra at viewing angle 41 (left) and 49 (right).

Measured irradiance spectra are typically contaminated with a few spikes. To illustrate this we compare the irradiance spectrum of orbit 5071, row 41 (Fig. 2.3, green), which causes a stripe with an amplitude of about +15 %, with the irradiance spectrum of orbit 4933, row 41 (red), which causes no stripe. The difference can hardly be noticed by eye (upper panel).

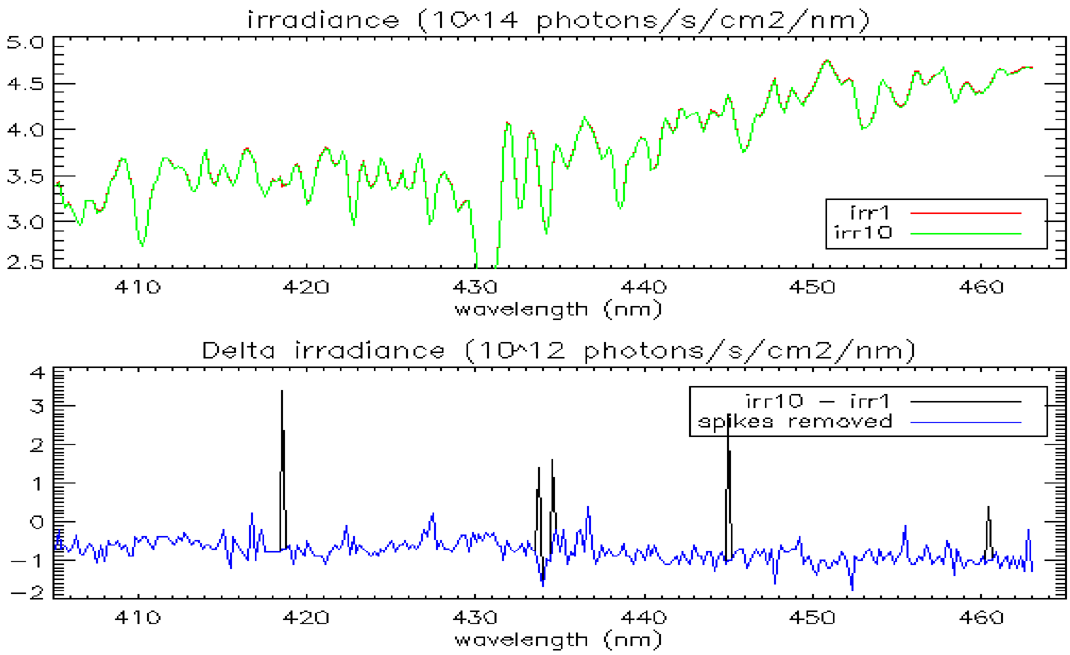

Fig. 2.3 Irradiance spectra of orbit 4933 (red) and orbit 5071 (green) at row 41 and modified spectrum of orbit 5071 where spikes in the difference spectra are removed (blue).

The difference spectrum (lower panel, black) shows spikes at various wavelengths with amplitudes of up to 1%. Removing the spikes in the difference spectrum (blue) largely removes the stripe in the data from orbit 5071. It has been shown that single spikes in the irradiance with an amplitude of 1% can cause errors in the retrieved NO_2 column of up to 20 %; the amplitude of the error depends on the spectral position of the spike and is determined by the differential absorption spectrum of NO_2 [RD2].

The impact of dark signal changes that remain constant after the actual change has taken place can be mitigated by updating the dark signal data in the OPF. RTS pixels have to be discarded from the processing and are flagged as erroneous using an RTS pixel mask [RD6]. Transient pixels are flagged as erroneous in the GDPS for individual measurement frames [RD4, RD5].

2.2 Diffuser features

A quartz volume diffuser (QVD) is used for solar irradiance measurements in order to achieve a homogeneous illumination of the detector array. The solar irradiance measured via the QVD depends on the goniometry (solar azimuth and elevation angle), the row, and the column (wavelength) of the detector array. The dependence on the goniometry and the row is largely corrected for by the so-called *delta irradiance* correction (dIRRAD) [RD3]. The wavelength dependence is small and is currently not corrected for. The reflectance as a function of wavelength exhibits a variety of structures including wiggles (referred to as diffuser features in the following) with long periods (50 nm) and short periods (down to a few nm). The amplitude of these structures in individual frames with a nearly constant elevation angle can be as large as 0.5 %. Nominal irradiance products contain elevation-angle-averaged spectra. The amplitude of diffuser features in these spectra is estimated to be on the order of 0.2 %. These structures depend on the row and on the azimuth angle which has a slow seasonal dependence. Sinusoidal errors in the irradiance spectra with amplitudes of a fraction of a percent can introduce errors of ten percent and more in the retrieved atmospheric column data for NO_2 [RD2]. Diffuser features are therefore a potential cause for stripes. Note that diffuser features with very long periods are compensated for by the low-order polynomial that is fitted to the reflectance in the DOAS fit. Features with shorter periods can cause stripes. These features cannot be filtered out efficiently using spectral filtering techniques, mainly because of the similarity to the spectral features of the NO_2 cross section. As a result of the varying nature of the diffuser features it is not possible to correct for them in the level 0 to level 1 data processing.

2.3 Noise

The signal-to-noise ratio of irradiance spectra of operational irradiance products varies between 1000 and 6000 depending on the row and the wavelength. In Fig. 2.4 the signal-to-noise ratio (SNR) is shown for the wavelength range from 405 nm to 465 nm that is used for the NO_2 retrieval. The signal-to-noise ratio shown is valid for elevation-angle-averaged spectra and is derived from the series of irradiance spectra for individual elevation angles. The variance of the intensity signals are determined using various filtering techniques applied in order to remove trends that are induced by the elevation-angle-dependence diffuser features.

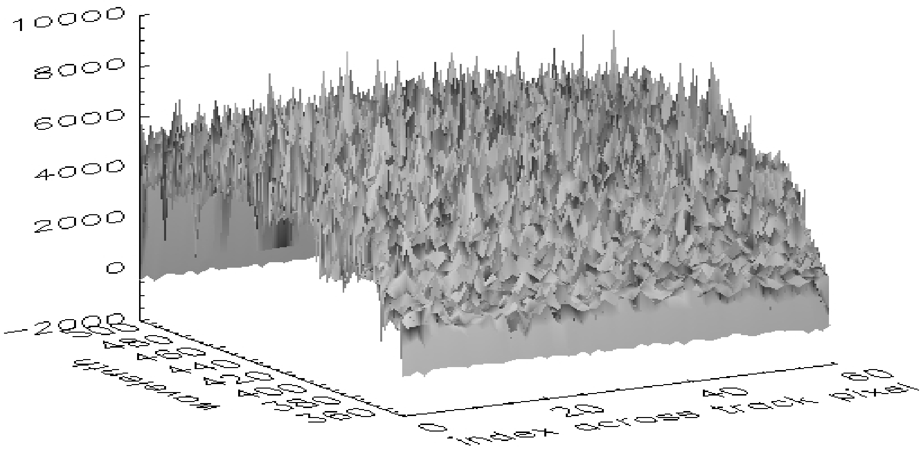

Fig. 2.4 Signal-to-noise ratio of irradiance measurement o6055 derived from 52 co-added spectra.

For irradiance measurements, the limiting factor for the SNR appears to be the discretization noise of the Analogue-to-Digital Converter (ADC). This holds for about 90 % of the data in the wavelength region considered which are processed using gain mode 3. The discretization induces a discretization noise with an amplitude of about 10^{11} photons/s/cm^2/nm/sr while the typical amplitude of the irradiance spectra is about $4x10^{14}$ photons/s/cm^2/nm/sr. Radiance measurements, which have larger intensity values, are assumed to be shot-noise limited. Outliers in the irradiance spectra due to noise are found to deviate from the average values by up to 1% and can hence introduce stripes.

Radiance and irradiance data are stored as integer values of mantissa (2 bytes) and exponent (1 byte) to the basis 10. Data are stored such that the mantissa takes values between 3277 and 32768. The rounding error implied limits the SNR to ~6500 in the worst case, i.e. for numbers with small mantissa values. If the basis 2 is used instead, the mantissa takes values between 16384 and 32768 and the rounding error is by a factor of 5 lower. Hence, if the basis 2 is used, the SNR is limited by effects other than the rounding error. A test has been performed where the irradiance data have been stored either as double precision float numbers or as mantissa and exponents values to the basis 2 throughout the data processing. A comparison with the nominal case shows that the NO_2 vertical column is insensitive to rounding errors implied by the data representation using the basis 10 in combination with 2-byte integer values for the mantissa.

2.4 Conclusion

Stripes are caused by a combination of effects including dark signal related errors, diffuser features and noise. The following table gives an overview of the impact of various error sources on the level 2 data.

Error source	Irradiance	Radiance
Dark current changes	stripes	stripes
RTS pixel not flagged	stripes	pixel-to-pixel variability
Transient pixel not flagged	stripes	pixel-to-pixel variability
Diffuser features	stripes	-
Noise	stripes	pixel-to-pixel variability

In general, all row dependent errors in irradiance products can cause stripes. This includes dark current changes that are not optimally corrected in the level 1 to level 0 data processing, RTS and transient pixels that are not flagged correctly, diffuser features, as well as noise. RTS and transient pixels errors as well as noise affect each radiance measurement of an orbit in a different way. Hence, radiance data that are affected by such errors do not cause stripes but increase the pixel-to-pixel variability in the level 2 data. All dark signal related errors, such as dark signal changes, RTS and transient pixel errors, as well as additive noise components, have a larger impact on the irradiance data than on the radiance data due to the lower signal level of irradiance measurements.

3 Strategies for reducing stripes

In this section we discuss a number of measures to reduce the amplitude of the stripe patterns.

3.1 Updating calibration data

The ground-segment processing from level 0 to level 1B includes various calibration steps. The calibration data required are stored in the operational parameter file (OPF) and include dark signal data, RTS masks, etc. Currently the OPF is updated on a monthly basis in order to account for changing dark currents of the detector pixels. In view of the relatively fast time dependence of dark signals (see section 2.1) it has been decided to generate an updated OPF for each day (time-dependent OPF) using the most up-to-date dark signal data.

Figure 3.1 shows the impact of updating the dark signal data for irradiance and radiance data of orbit 6055 (blue) as well as for the irradiance data only (green).

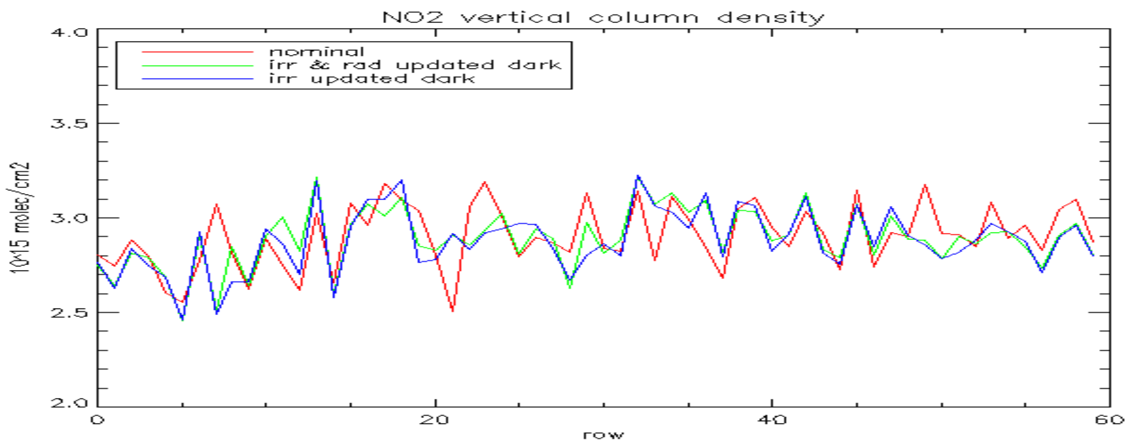

Fig. 3.1 NO_2 vertical column density (molec/cm^2) from radiance and irradiance data processed with dark signal data from the same orbit 6055 (blue) compared to the nominal case (red) and to a case, where only the irradiance data is processed with updated dark signal data (green).

The amplitude of the strongest stripe at row 21 is clearly reduced whereas stripes with smaller amplitudes remain largely unchanged. The stripe pattern is more sensitive to a dark signal update in the irradiance data than to dark signal updates in the radiance data. This can be explained by the lower signal level of the irradiance measurements.

An improved transient pixel flagging algorithm has been implemented in the GDPS (version 0.9.13 and higher) [RD4, RD5]. An algorithm for generating improved RTS pixel masks based on in-flight data is applied since September 2005 (OPF version 25 and higher) [RD6]. OMI level 1B data processed with OPF version 25 or higher and GDPS 0.9.13 or higher contain reliable pixel quality flags for RTS and transient pixels. Fig. 3.2

shows the relative deviation from the reference, i.e. the optimal case, when the improvement on the dark signal data (black) or the improvement on the RTS flagging (green) is made undone.

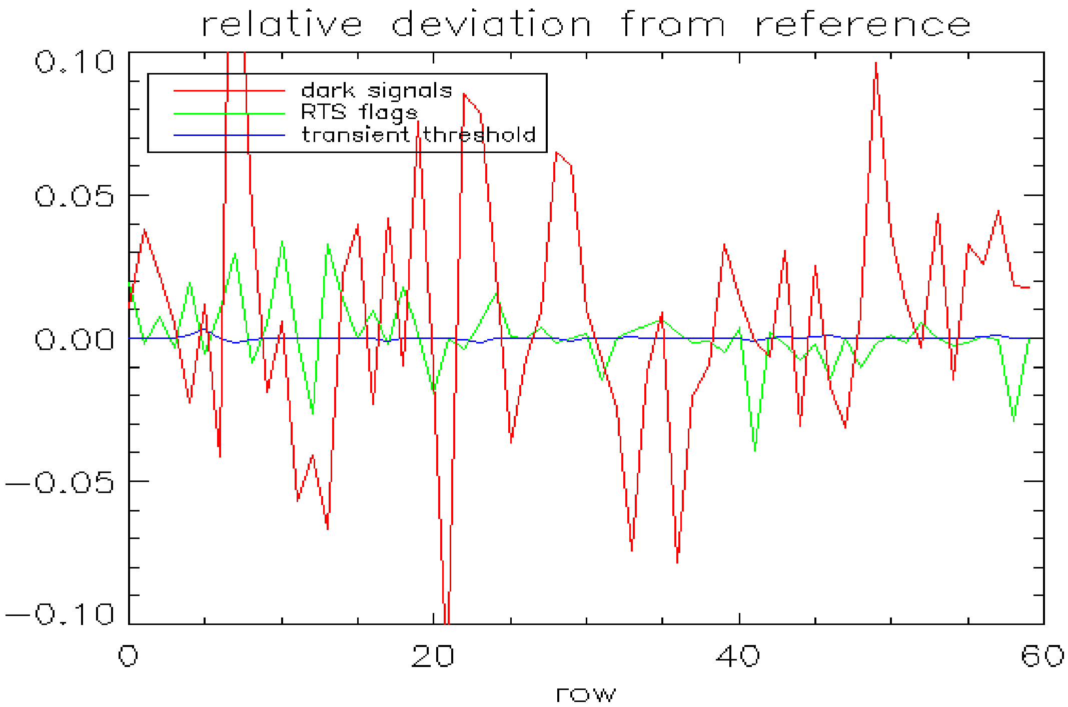

Fig. 3.2 Relative deviation of the NO_2 columns from the reference case (shown in red in Fig. 3.4). The impact of using updated dark signal data (black) is compared with the impact of using correct RTS flags (green), and with the impact of using a low threshold for transient flagging (blue).

Updating the dark signal data appears to have the relatively strongest impact. Dark signal errors are responsible for large errors with amplitudes of 20 % peak to peak. The impact of RTS-masking is lower. Ignoring RTS behaviour of detector pixels causes errors of up to 10 % peak to peak. In an additional test the threshold value for transient pixel flagging has been set to a value lower than the nominal one. This reduces the chance that transient pixels remain unflagged. The impact of using a transient threshold value lower than the nominal one (blue) appears to be negligible.

3.2 Time-averaging irradiance spectra

The spectral features that cause stripes vary from measurement to measurement. In view of this variability it can be expected that averaging irradiance spectra reduces stripes. Averaged irradiance spectra using a simple mean filter can be extracted from the KNMI Trend Monitoring and Calibration Facility (TMCF). A median filter is expected to provide slightly better results than a mean filter since the median value of a distribution is less sensitive with respect to outliers. Currently, median filtered data have to be calculated off-line (because of the serial data processing in the GDPS). Before applying a median filter, trends have to be removed from the data set. In order to achieve this, a sun distance correction is applied. Furthermore, slow spectral structures in the irradiance spectra (possibly diffuser features) are filtered out. This does not influence the retrieved column data since these structures are compensated by the low-order polynomial in the DOAS fit.

Averaging irradiance data processed with nominal dark signals (not updated) over periods of months does not reduce the amplitude of the stripe pattern significantly. This has been shown using average irradiance spectra for long time series (up to 6 months) that have been extracted from the TMCF. In contrast, improvements can be achieved by using median and mean filtered irradiance data if they have been processed using updated dark signal data, improved flagging algorithms and an improved dIRRAD correction (using OPF 27). Results for median filtered and mean filtered irradiance products are very similar. Results for median filtered irradiance products from such data are discussed in Section 4.

3.3 Composite Irradiance Product

A composite irradiance product is composed out of a selection of irradiance spectra from a number of input irradiance products. The selection criteria for the irradiance spectra are based on level 2 column density data retrieved from the irradiance data and the radiance data from the same orbits and are explained briefly in the following:

First, the stripe patterns in the column density data are identified using the along-track median of the column density data of each orbit. Stripes are defined as along-track median values that deviate from the total median by more than the along-track standard deviation (see also Section 1). A low order polynomial function of the row number is fitted to the stripe pattern (i.e. the along-track median) of each orbit. Dividing the stripe pattern by this polynomial function removes across-track trends and brings the stripe patterns of all orbits to a common baseline. For each row, the irradiance spectrum is selected that causes the stripe with the smallest possible amplitude or no stripe at all (Fig 3.3).

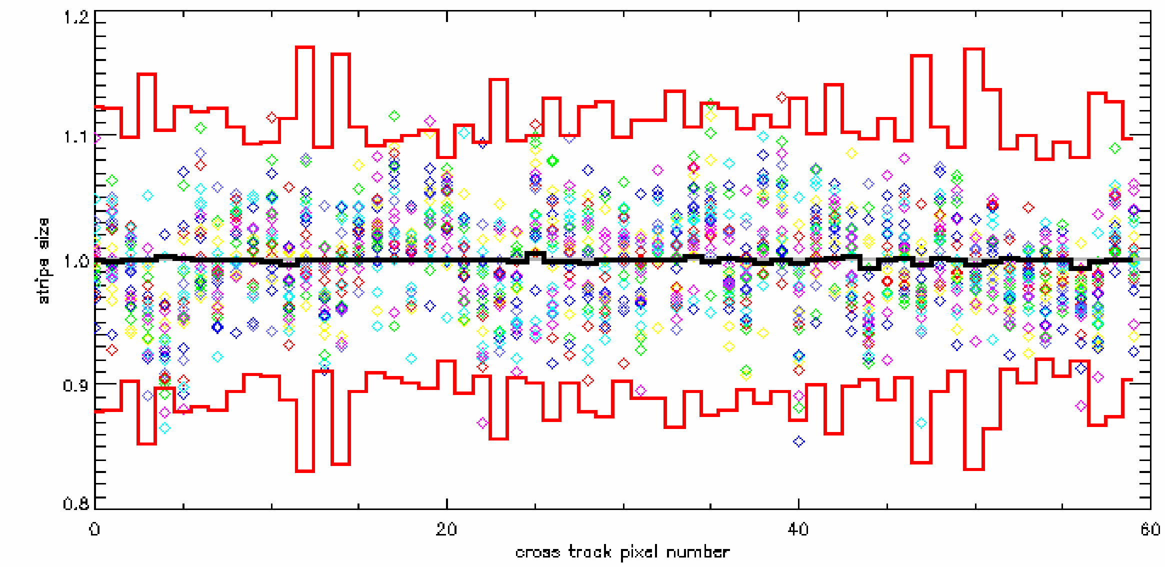

Fig. 3.3 Relative deviation of NO_2 column data from a common baseline. Data from 25 orbits are shown in coloured diamonds. The spectra that correspond to the smallest deviations (black) are chosen for the composite irradiance product. When the composite irradiance product is applied the remaining stripes are much smaller than the along track variability of the NO_2 column data shown (+/- 1σ, red).

Note that the spectra of the input irradiance products are corrected for sun distance variations. This correction has no impact on the retrieved column data. The correction is made in order to facilitate the comparison with other irradiance products.

A composite irradiance product is generated from level 1B data (processed with OPF 25) using level 2 data (processed in the OMI data processing system (ODPS) taken from …/offline/ODPS/v002/OMNO2A) from October and from July 2005. NO_2 vertical column data of orbit 6674 (October) processed with these composite irradiance products are compared with data processed with a standard irradiance product of this orbit.

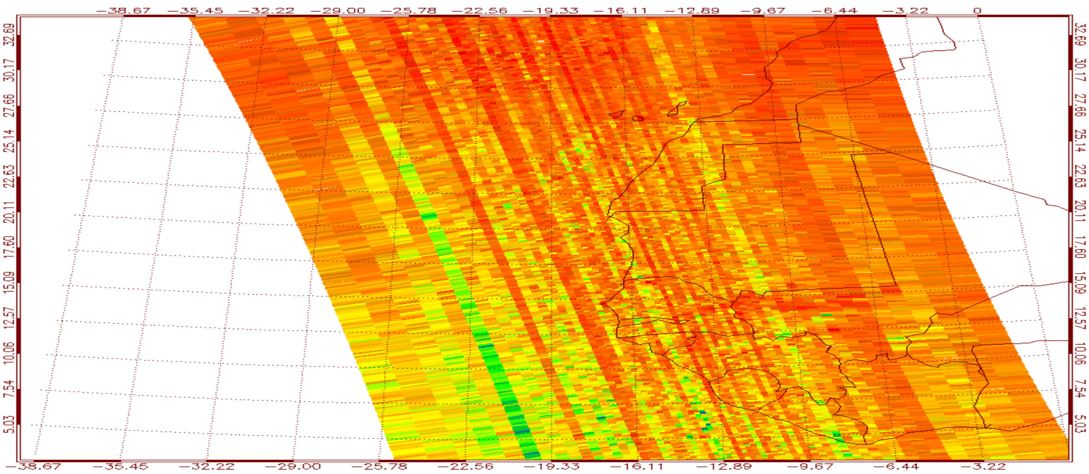

Fig. 3.4 NO_2 vertical column data of orbit 6674 processed with a standard irradiance product

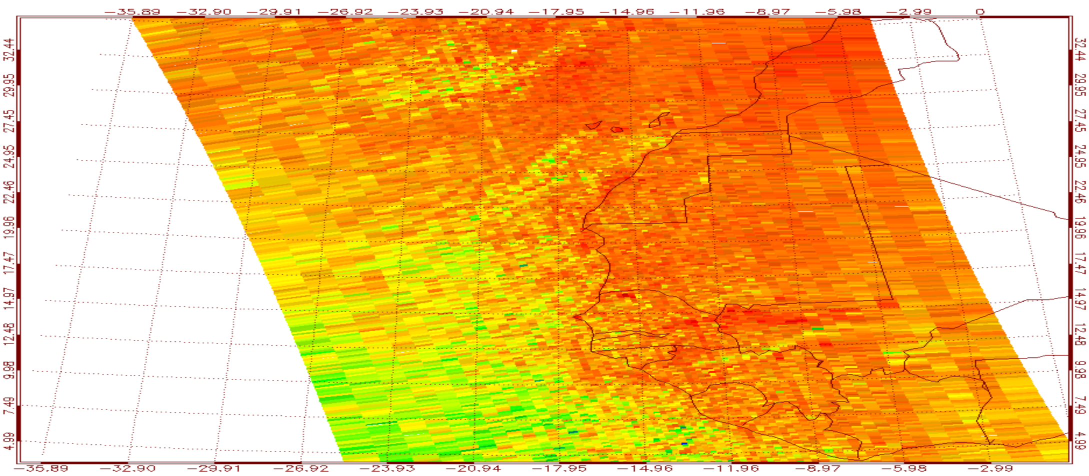

Fig. 3.5 NO_2 vertical column data of orbit 6674 processed with a composite irradiance product based on data from October 2005.

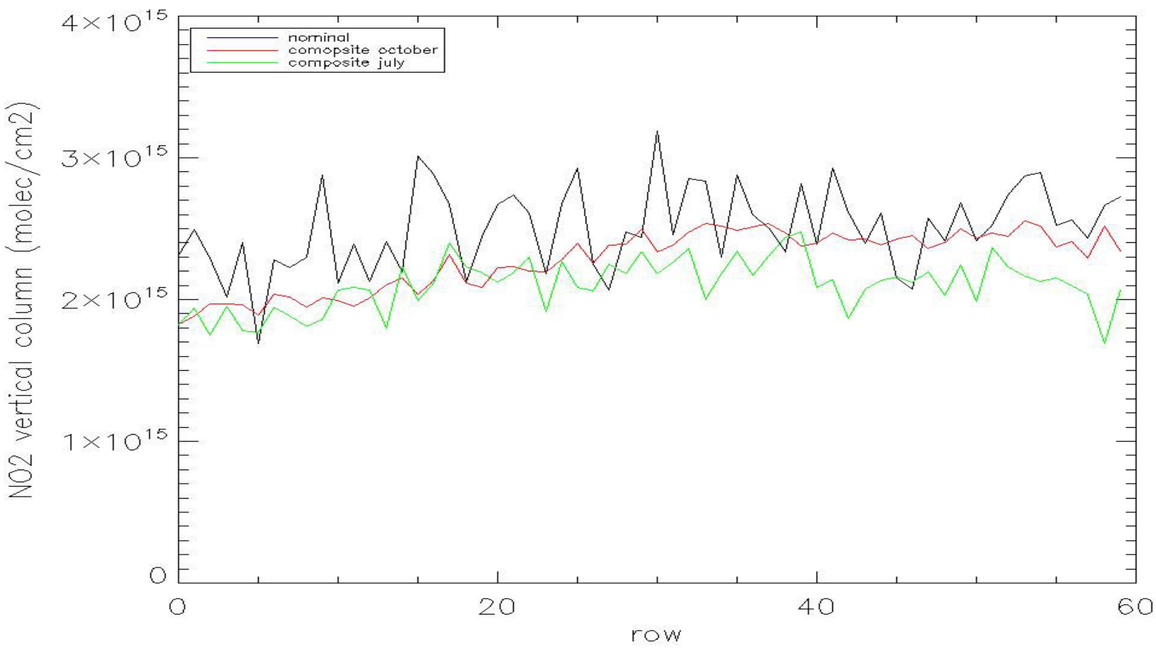

Fig. 3.6 NO_2 vertical column data of orbit 6674 processed with the nominal irradiance (black) and with the composite irradiance products from July (green) and October 2005 (red).

The NO_2 vertical column using the standard irradiance product shows a pronounced stripe pattern (Fig. 3.4). The stripe pattern is nearly absent when the composite irradiance product is used that is generated using data from October 2005 (Fig. 3.5). The improvement is less when a composite irradiance product is used that is based on data from July 2005 (Fig. 3.6). This is due to the fact that dark signals and the diffuser features change in time, while the data set from October comprises the orbit 6674.

The composite irradiance strategy outlined above is based on the level 2 data from a standard forward processing stream that are based on irradiance and radiance data from the same orbit. The composite irradiance product yields slightly better results when the input irradiance products are processed with one common radiance product. The drawback of this approach is that it requires an additional level 2 reprocessing step for generating the composite irradiance product. Another possible drawback is that the obtained composite irradiance product may be more specific to the radiance data used. Therefore, it may be inferior to the nominal composite when applied to other radiance data.

A composite irradiance product that has been derived for one product (e.g. for the NO_2 vertical column density) is not applicable to other products (e.g. for O_3). When the composite irradiance product is applied for level 2 processing one should use the same PGE and the same settings that have been employed to generate the input column data for the selection of the irradiance spectra.

A composite irradiance product that has been generated from irradiance data measured within a period of one month is applicable to radiance data measured in a time range of at least one month before and after. If level 1B data are used that have been processed using updated dark signal data, a composite irradiance product is applicable for data of one year or more.

3.4 Other approaches

In this section, a few approaches are discussed shortly that look promising but do not reduce the overall amplitude of the stripe pattern.

3.4.1 Discarding outliers

Outliers are identified in the fit-residuals, i.e. the difference between the measured reflectance and the optimal fit from the NO_2 retrieval. A residual value is considered as outlier if it exceeds a threshold fraction of the measured reflectance. First the NO_2 retrieval is applied in order to identify outliers. In a second run of the NO_2 retrieval these outliers are discarded. The results of this procedure is shown applied for three orbits (Fig. 3.7):

- o07216, where RTS flags and transient flags are not used (upper graphs),
- o04940, where RTS flags and transient flags are used (lower graphs),
- o06055, where RTS flags and transient flags are used and the dark current data are updated (graphs in the middle).

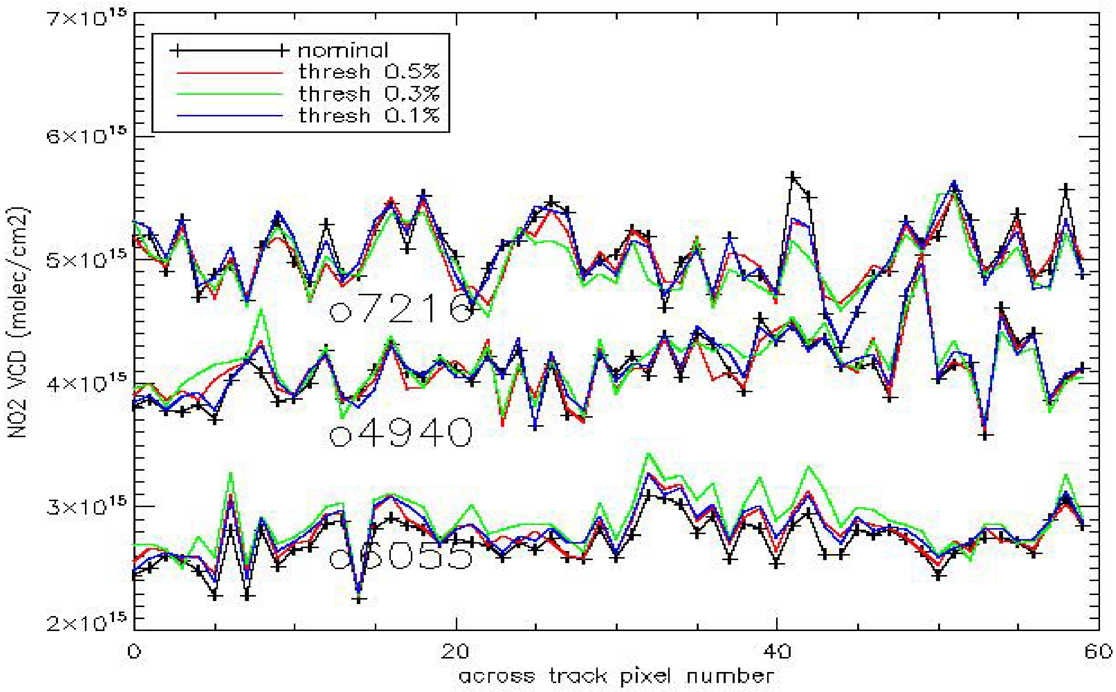

Fig. 3.7 Retrieved NO_2 columns using various outlier thresholds.

Globally seen, a threshold value 0.3 % appears to work better than the other values tested, i.e. 0.1 % and 0.5 %. Discarding outliers tends to reduce stripes in some cases (e.g. o7216 row 40-45; o6055 row 30-35), whereas many pronounced stripes are not reduced in amplitude. New stripes are introduced (e.g. o4940 row 8, 23; o6055 row 6, 21) as well as offsets (o6055 all rows). Discarding outliers appears to be beneficial if the level 1B data processed with OPF version 17 and older are used. If currently available calibration data (including e.g. RTS- and transient-flagging masks) and updated dark signal data are used for the level 1B processing this approach hardly reduces the stripes.

3.4.2 Row-averaging irradiance spectra

An irradiance product is produced by averaging irradiance spectra from different rows. The idea is that row-specific features causing stripes average out. Spectral interpolations are necessary before averaging since the wavelength grids of different rows are shifted with respect to each other (spectral smile). In order to keep the errors due to the spectral interpolation as small as possible, only the spectra of neighbouring rows are averaged. Since the impact of this procedure is small, it is applied iteratively.

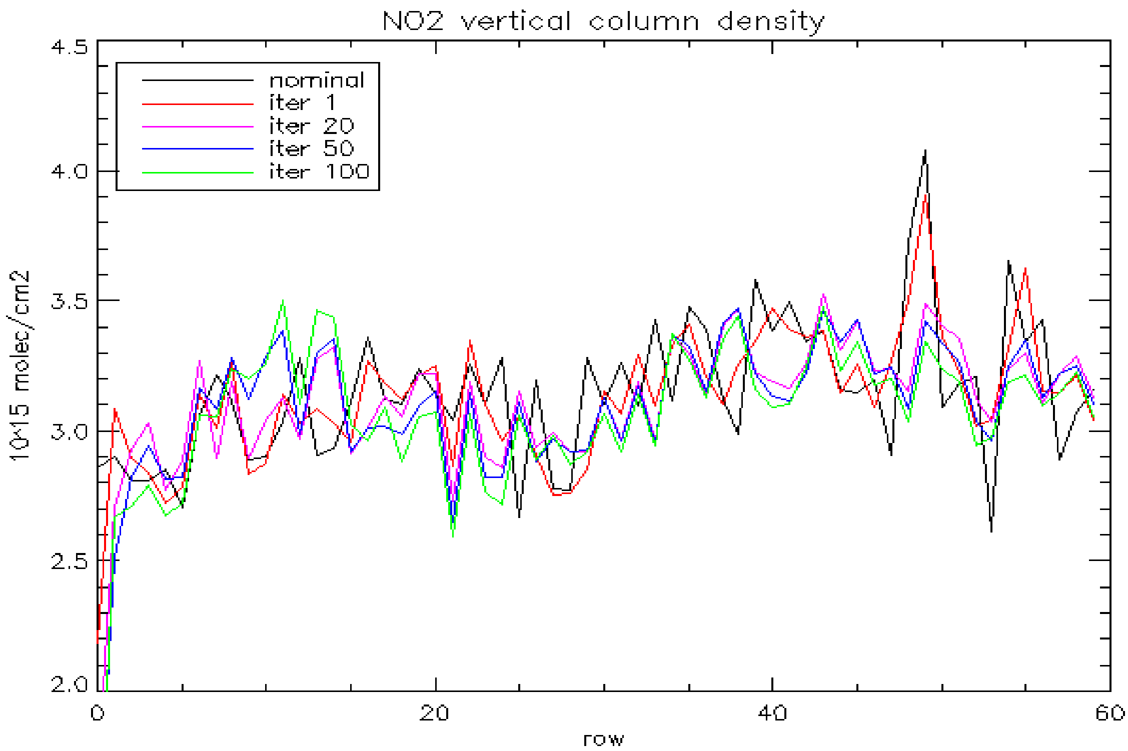

Fig. 3.8 NO_2 vertical column density for orbit 4940 using iteratively row-averaged irradiance.

At many rows the averaging procedure reduces stripes when it is applied up to 100 times (Fig. 3.8). Unfortunately this causes the appearance of new stripes at some rows. We attribute this effect to row-specific errors in the dark signal or other calibration parameters in the radiance. Row-averaging is therefore not considered an efficient technique to reduce the stripes.

4 Application

The strategies discussed in Section 3 are applied to a set of Level 1B data of 25 orbits that have been reprocessed using dark signal data from the same orbit as the light measurements, using improved pixel flagging, and an improved dIRRAD correction as defined in OPF 27. The high-sampling is applied in the level 2 processing for the spectral interpolation of the irradiance spectra. This method is based on a high resolution reference sun spectrum and is considered the best available interpolation method. The data processed comprise data from 4 periods:

	Time range	azimuth angle range
Period 1	2 nov 2004 - 20 feb 2005	30º - 23º
Period 2	29 oct 2004 - 5 nov 2004	constant 31º
Period 3	8 jul 2005 - 3 nov 2005	18º - 30º
Period 4	30 oct 2005 - 8 nov 2005	constant 30º
Period 'global'	All	All

Each period contains about 7 orbits including radiance and irradiance measurements. Period 1 and 3 are chosen such that the irradiance measurements cover a wide range of solar azimuth angles, whereas period 2 and 4 comprise measurements with nearly the same solar azimuth angle. The periods 1 and 2 are early in the mission period and are therefore less affected by radiation damage which is referred to as 'global'.

Composite irradiance products, median and mean irradiance products are derived from the level 1B data from each period separately as well as for the complete data set as a whole. Composite irradiance products are generated for the NO_2, the O_3, and the O_2-O_2 cloud product using level 2 data of each product respectively. Median and mean filtered irradiance products are generated from (already elevation-angle-averaged) spectra from various irradiance products as explained in Section 3.2.

In this section we compare level 2 data (based on reprocessed level 1b data) using composite, median, and standard irradiance products, with level 2 reference data that have been processed with nominal settings (OPF 25). Since the difference between data using mean or median filtered irradiance data is small we do not show results based on mean filtered data. The reference data have been processed at the OMI Dutch processing site (ODPS) and are available on the MOS (/fa/omi/sat/aura/omi/offline/ODPS/v002/).

4.1 Results for NO_2

Composite irradiance products and median irradiance products are derived from the level 1B data from each period separately as well as for the complete data set as a whole. Level 2 data for the NO_2 vertical column is used for the composite irradiance product.

Reprocessing the data using improved dark signal data, pixel flags and an improved dIRRAD correction significantly reduces the stripes (Fig 4.1 red, Fig 4.2 upper right). The amplitudes are by factor of about 2 lower than in the reference data (Fig 4.1 black, Fig 4.2 upper left) that are processed with nominal settings (OPF 25). Using a median filtered irradiance product from the reprocessed data of all 25 orbits further improves the situation (Fig 4.1 green, Fig. 4.2 lower left). Results from irradiance products generated using median filtered data or mean filtered data (not shown) are similar in their error amplitude. The amplitude of stripes is reduced by a factor of about 5 (as compared to the nominal case) if a composite irradiance product is used that has been generated from the reprocessed data for all 25 orbits (Fig 4.1 blue, Fig. 4.2 lower left). The improvements that can be achieved by the composite irradiance approach and the median irradiance approach are comparable.

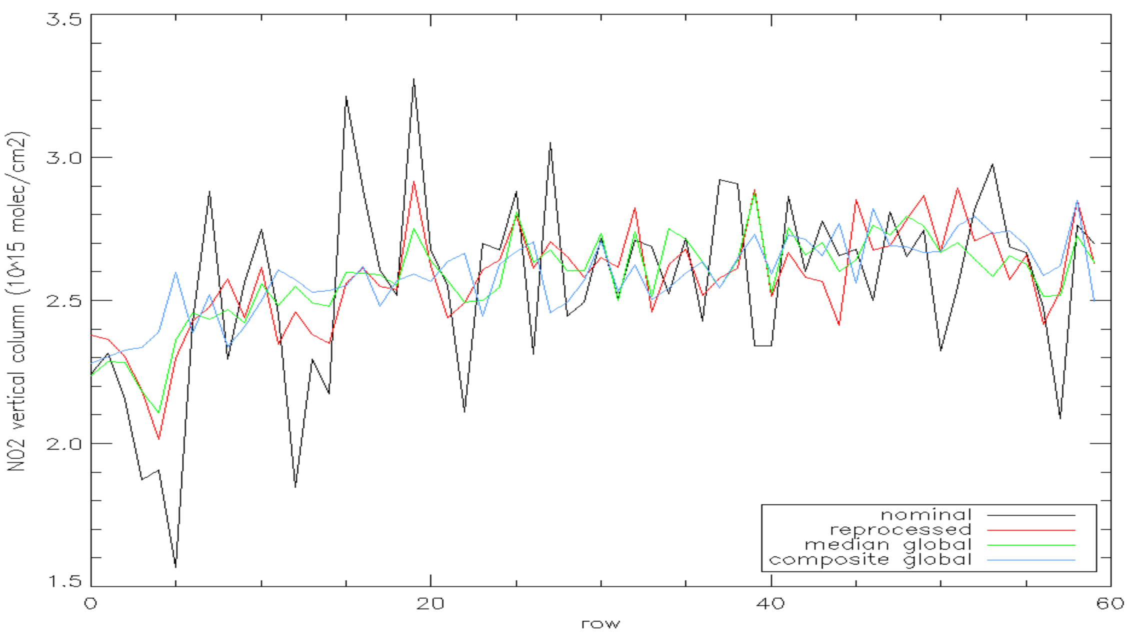

Fig. 4.1 Along-track median of the NO_2 vertical column density for orbit 6935 with latitudes ranging from ~-40° to ~+10°. Nominal data (black) are compared with reprocessed data using the standard irradiance (red), a median filtered irradiance (green), and a composite irradiance product (blue).

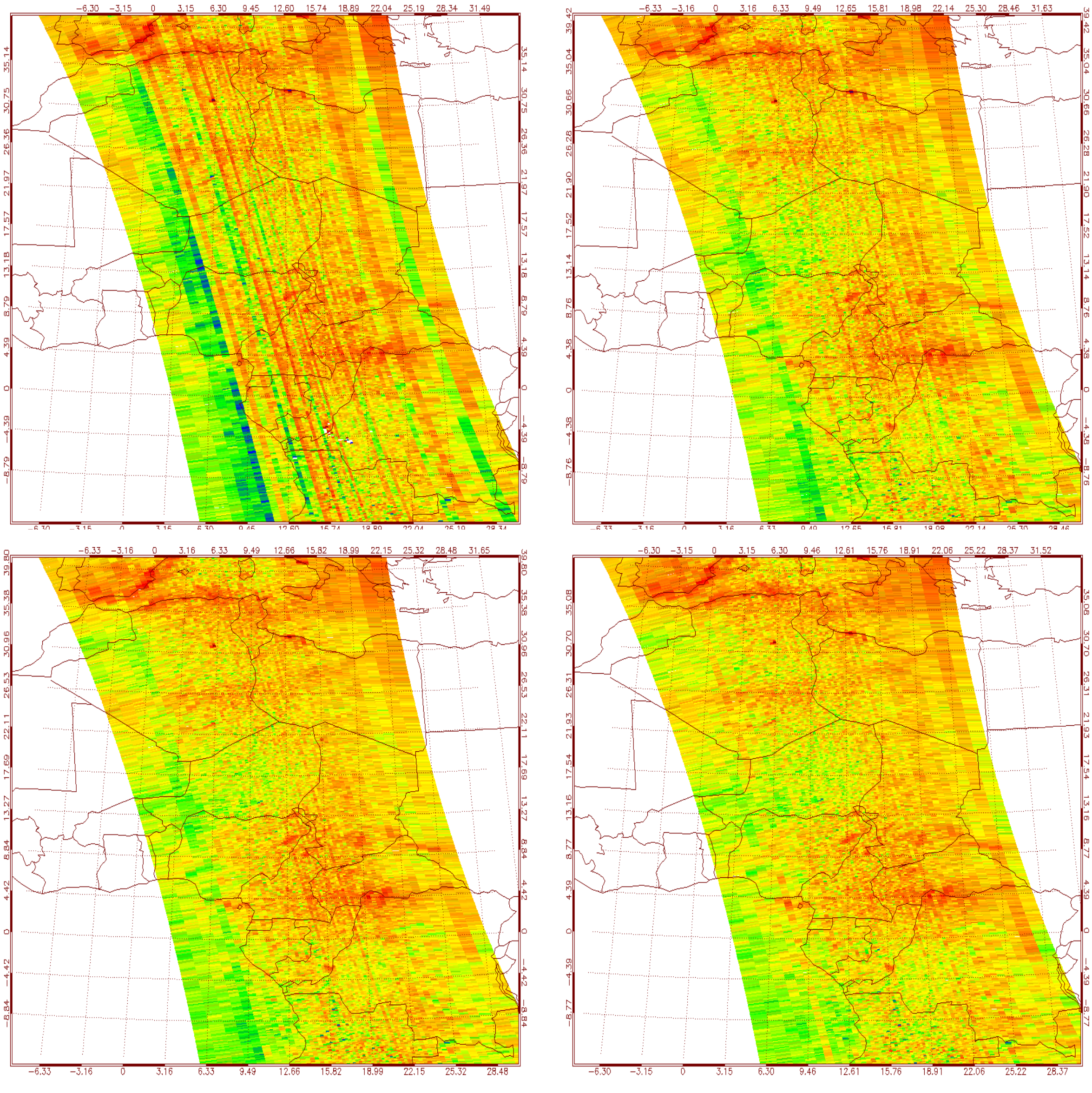

Fig. 4.2 NO_2 vertical columns for orbit 6935. Nominal data (upper left) are compared with reprocessed data using the standard irradiance (upper right), a median filtered irradiance (lower left), and a composite irradiance product (lower right).

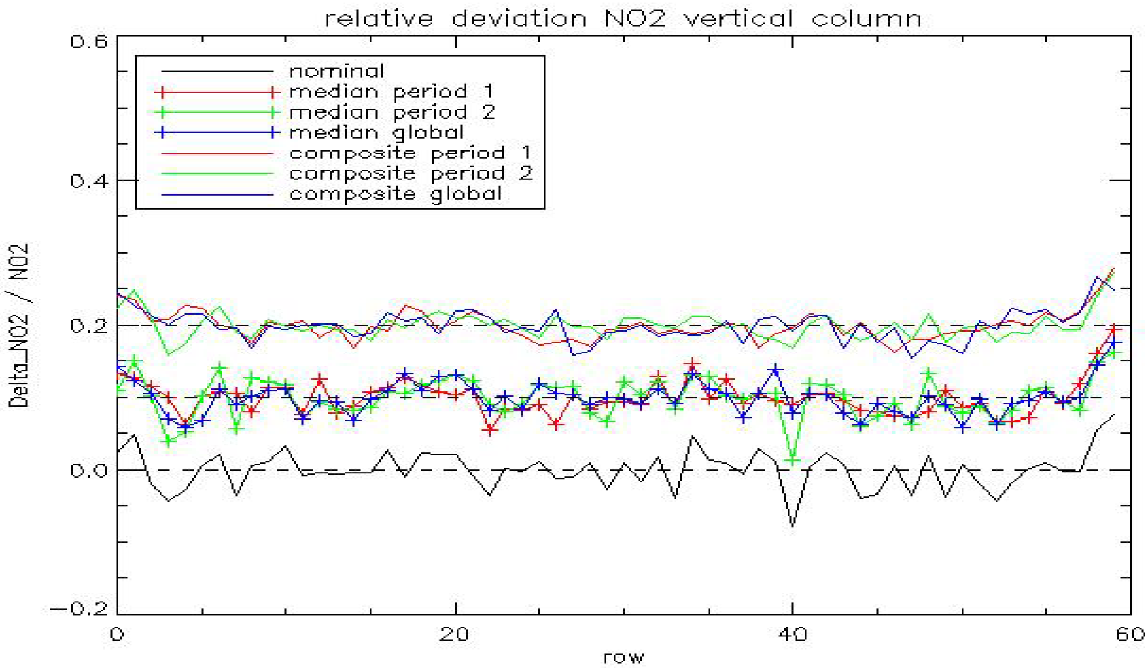

Fig. 4.3 Relative deviation from the median of the NO_2 vertical column for orbit 1604 processed using the nominal irradiance, and with the median irradiance and the composite irradiance products from period 1 and 2. An offset of 0.1 (0.2) is applied to the results using the median (composite) irradiance for clarity. Data for latitudes ranging from -60° to -50° are shown.

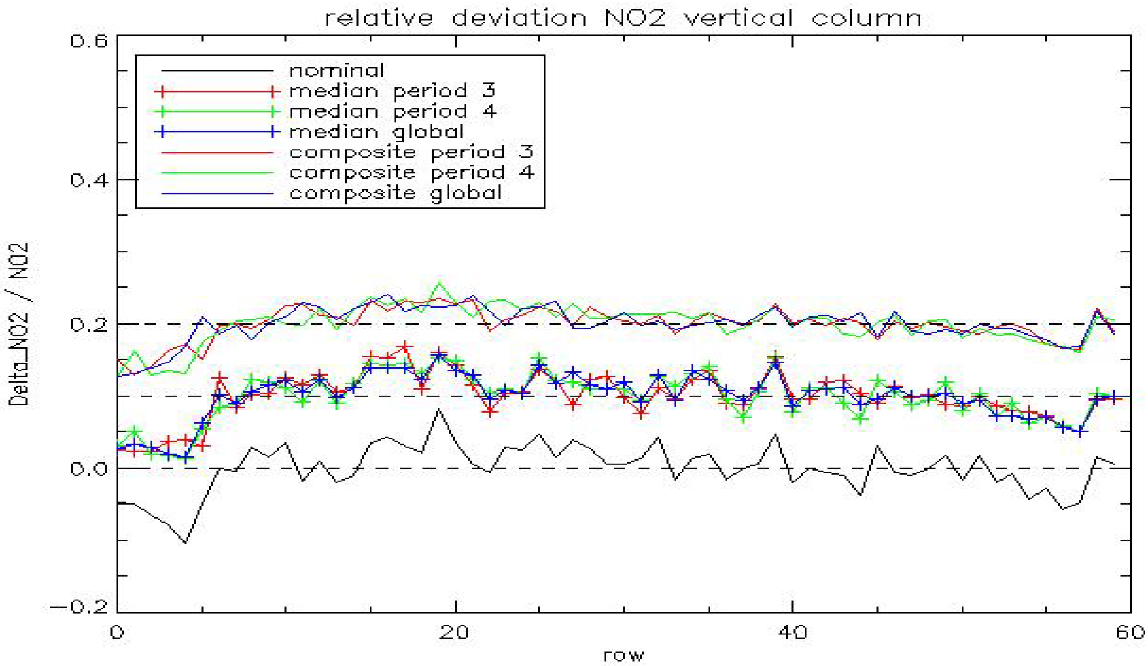

Fig. 4.4 As above for orbit 6935 and the periods 3 and 4.

Diffuser features depend on the azimuth angle. Hence, one may assume that irradiance products based on spectra with a variable azimuth angle provide data with smaller stripes as compared to irradiance products from data with a constant azimuth angle. Comparing results from data with a constant azimuth angle, i.e. from periods 2 and 4 (Fig. 4.3 and 4.4, green), with result for other cases, i.e. using data from periods 1 and 3 (red) and global (blue), this appears not to be the case. This suggests that the remaining stripe pattern is mainly driven by features other than the ones caused by the azimuth angle dependence of the diffuser reflectance. The stripe pattern in the data from period 2 and 4 are similar in amplitude. The radiation damage that occurred in one year's time (between period 2 and 4) does not increase the stripe amplitudes. Hence, radiation damage is not a major factor causing stripes when reprocessed data are used. The remaining stripes could be caused by noise. Further improvements can be expected when a larger data set is available for generating composite or median irradiance products.

4.2 Results for other products

Figure 4.5 shows the improvements that can be achieved for the O_2-O_2 slant column (upper panel) and the cloud top pressure data (lower panel) of the OMI cloud product OMCLDO2 for orbit 3207. The cloud product appears to be largely insensitive with respect to the improvements in the dark signal data, the RTS pixels masks and the dIRRAD correction that are taken into account in the reprocessing (black and red). This suggests that the stripes shown are mainly caused by noise in the irradiance data. Stripes are nearly absent when median-filtered irradiance data are used (green) or when a composite irradiance product is applied that has been derived from the O_2-O_2 slant column data (blue).

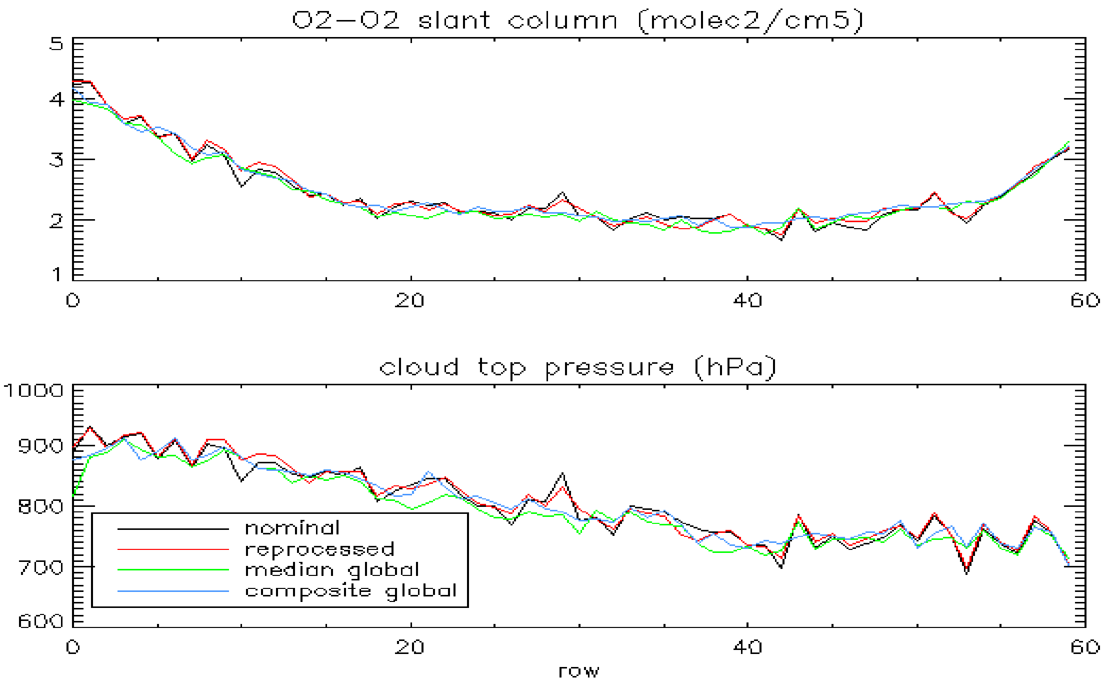

Fig. 4.5 O_2-O_2 slant column (upper panel) and cloud top pressure data (lower panel) of orbit 3207. Nominal data (black) are compared with reprocessed data using the standard irradiance (red), a median filtered irradiance (green), and a composite irradiance product (blue).

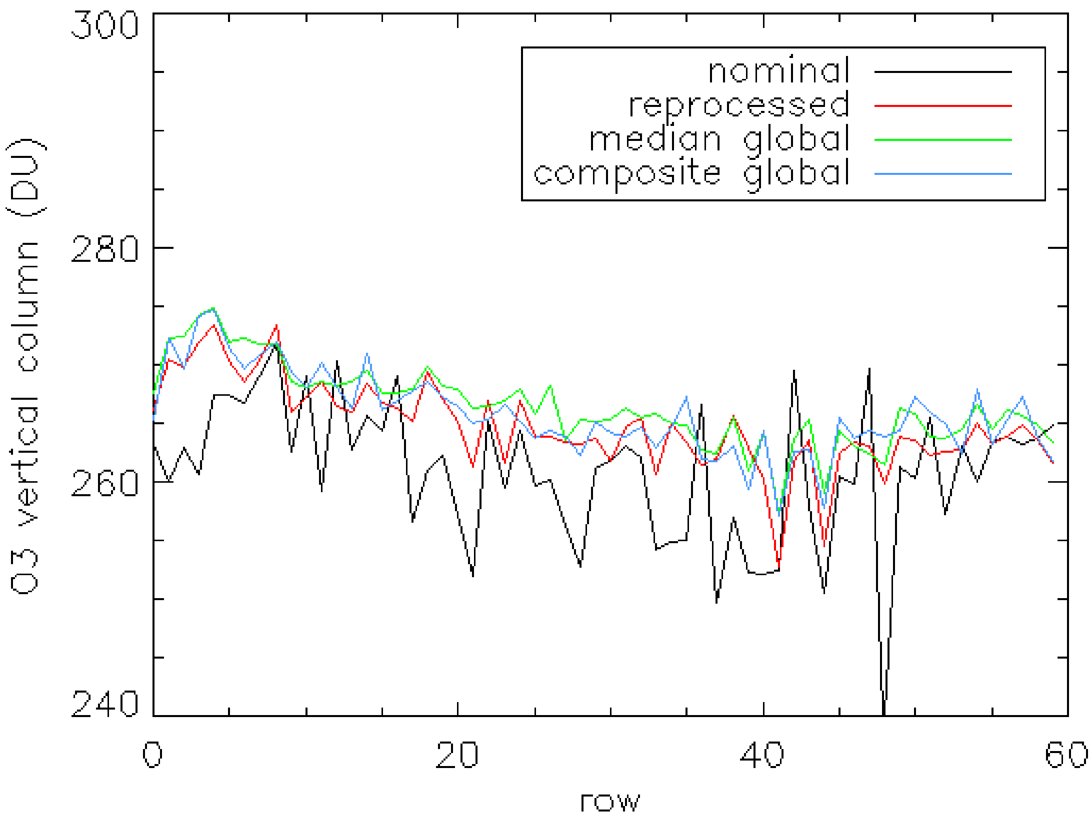

Fig. 4.6 O_3 vertical column of orbit 6935. Nominal data (black) are compared with reprocessed data using the standard irradiance (red), a median irradiance (green), and a composite irradiance product (blue).

The O_3 vertical column data exhibit stripes with amplitudes up to 20 % (Fig. 4.6, black) when being processed nominally. The stripes are significantly reduced by using improved dark signal data, pixel flags and an improved dIRRAD correction (red). Further improvements can be achieved by using a median irradiance (green) or a composite irradiance product (blue). Remaining stripes have amplitudes of up to 3 %.

5 Conclusions

The along-track stripes that appear in OMI level 2 data for various data products have been analyzed. The most important error sources have been identified that contribute to these artifacts. These error sources include

1. Changes in the detector pixel dark signal that are not optimally corrected,
2. Random Telegraph Signal (RTS) pixels and transient pixels that are not flagged correctly,
3. Diffuser features,
4. Noise in the irradiance measurements.

A variety of measures have been discussed that can be applied to reduce the amplitude of the stripes such as

1. Including updated dark signal data in the Operational Parameter File (OPF),
2. Applying improved flagging algorithms to mask out transient [RD4, RD5] and RTS pixels [RD6],
3. Using an improved delta irradiance correction (dIRRAD) [RD3] to reduce diffuser features,
4. Time-averaging (mean or median) irradiance spectra to mitigate the impact of all error sources mentioned above,
5. Using a composite irradiance product.

It has been shown that applying a combination of the measures 1, 2, and 3 leads to a significant reduction of the stripe pattern. Diffuser features and detector radiation damage currently seem to be minor factors in the appearance of the stripes after the above corrections have been applied. With the current state of the OMI instrument, noise seems to be a limiting factor that hampers further reduction of the stripes. In general, the amplitude of stripes can be further improved when time-averaged irradiance products are used. Using median or mean filtered irradiance data leads to comparable results. The best improvement can be achieved when a composite irradiance is used.

The improvement achieved depends on the data product, the orbit and the row. For NO_2 and O_3 data, remaining stripes are usually by a factor of 2 smaller than before, whereas the improvement achieved for the cloud O_2-O_2 product is somewhat smaller.

6 Implementation

It is envisaged to implement various measures to reduce the stripes in the operational data using updated dark signal data, improved algorithms for RTS and transient pixel flagging stream (see Section 3.1). The Ground Data Processing Software (GDPS) has been updated with improved algorithms for dIRRAD correction and for the flagging of transient pixels. The time-dependent OPF will assure that the GDPS always has the most up-to-date calibration data at its disposal; these data include, amongst others, dark current maps and RTS masks. The combination of the updated GDPS and the time-dependent OPF will be used to process OMI data from 2006 onwards and also to reprocess all other OMI measurements available.

Time averaged irradiance products using a standard mean filter are generated by the KNMI Trend Monitoring and Calibration Facility (TMCF). It is expected that the amplitudes of the stripes can be reduced by up to a factor 2 when using such time-averaged irradiance data, provided that both radiance and irradiance data were processed with the updated GDPS and the time-dependent OPF.

We also mention two other strategies to reduce stripes that can be used off-line, i.e. outside the operational data stream. Firstly, irradiance spectra can be time-averaged using a median filter, which is slightly less sensitive with respect to outliers than a standard mean filter (see Section 3.2). The median irradiance approach is most efficient when a large number of level 1b irradiance products are available that are processed with the updated GDPS and the time-dependent OPF. Secondly, a composite irradiance product can be generated for a specific data product using level 1b irradiance data as well as level 2 data (Section 3.3). The improvements that can be achieved by the composite irradiance approach and the median irradiance approach are comparable. However, making a composite irradiance is a huge effort that includes the analysis of Level 2 data products, whereas making a median irradiance is much more straightforward and can be done directly from the Level 1B.